PI 30.24-1

Electrical Equipment - Course PI 30.2

MOTORS

OBJECTIVES

On completion of this module the student will be able to:

1. Briefly explain, in writing, "shaft rotation" as an interaction of stator and rotor magnetic fields.
2. Draw and properly label the characteristic curves of the squirrel cage induction motor for:
   a) torque vs speed;
   b) current vs speed.
3. Explain briefly, in writing, the following terms, as related to a squirrel cage induction motor:
   a) Torque;
   b) Starting torque;
   c) Running torque;
   d) Pull out torque.
4. State, in writing, that the starting current is about = 6 x full load current.
5. Briefly explain, in writing, the following terms, as related to a squirrel cage induction motor:
   a) Motor full load current;
   b) Synchronous speed including the mathematical expression for synchronous speed;
   c) Slip speed, including the mathematical expression for slip speed.
6. Briefly explain, in writing, the meaning of the following nameplate data for a squirrel cage induction motor:
   a) HP
   b) RPM
   c) Volts
   d) Cycles
   e) Amps
   f) Phase
   g) Service Factor
   h) Time rating
   i) Insulation Class
   j) Maximum Ambient Temperature

6. k) CEMA Designation
   l) Frame
   m) Type.

7. Recall, and briefly explain the two basic types of enclosures for squirrel cage induction motors and give an application for each type.

8. In writing, briefly discuss the difference between the two methods of cooling used in each type of motor enclosure.

9. Briefly, in writing, state the consequence of changing the phase sequence, in a three phase induction motor.

1. Introduction

This lesson will introduce the reader to:

(a) What is a motor.
(b) Introduction to basic motor theory.
(c) Motor characteristics.
(d) Motor nameplate data.
(e) Motor cooling.

2. What Is a Motor

A motor is an electromechanical device which converts electrical energy into mechanical energy. Input to the motor is electrical energy. Output from the motor is rotation of the motor shaft, which delivers the required torque to a load. Load on the motor can be anything that needs to be rotated.

3. Motor Theory

Refer to the explanation of magnetic affects of electrical current and principle of electromagnetic induction, in the lesson on "Generators".

3.1 Electromagnetic Force

Consider a conductor through which a current is flowing. See Figure 1, below.

Current going away from the reader, into the page. Current direction is represented by '+' (tail of an arrow.)

Current coming towards the reader, out of the page. Current direction is represented by '.' (head of arrow).

Figure 1

3.1 Electromagnetic Force (continued)

Now consider a fixed magnetic field and a conductor carrying current placed in the magnetic field. See Figure 2.

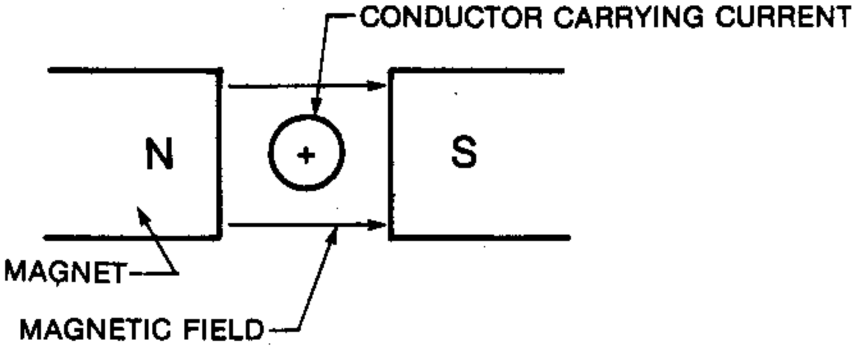

Figure 2: Current Carrying Conductor in a Magnetic Field

The direction of current in the conductor, as shown, is away from the reader, into the page.

When the current flows through the conductor, a magnetic field is developed around the conductor. The direction of the magnetic field can be determined by the right-hand rule. See Figures 3(A) and 3(B).

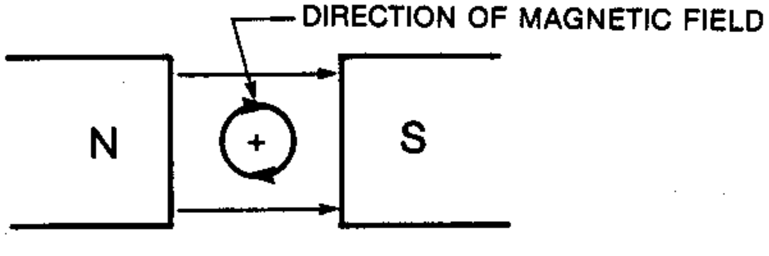

Figure 3(A): Magnetic Field Around the Conductor

3.1 Electromagnetic Force (continued)

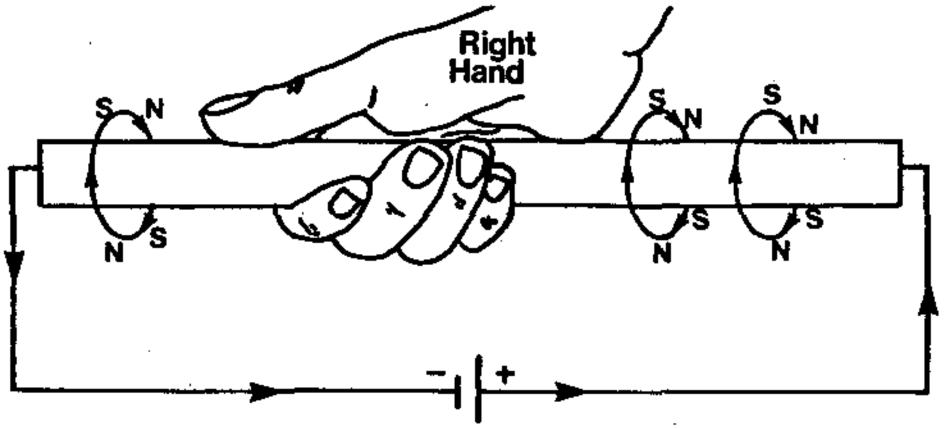

Figure 3(B): Right hand Rule for determining Direction of Magnetic Lines of Force around a Straight, Current-Carrying Conductor.

3.1 Electromagnetic Force (continued)

Now there are two magnetic fields (think of them as two forces) namely:

(a) Magnetic field from the permanent magnet.
(b) Magnetic field around the conductor due to the current flow through it. Interaction of the two magnetic fields is as follows:

- At the top of the conductor, the two fields are additive (in the same direction).
- At the bottom of the conductors, the two fields are subtractive (in the opposite direction).

As a result, the conductor, if free to move, will move in the downward direction. See Figure 4.

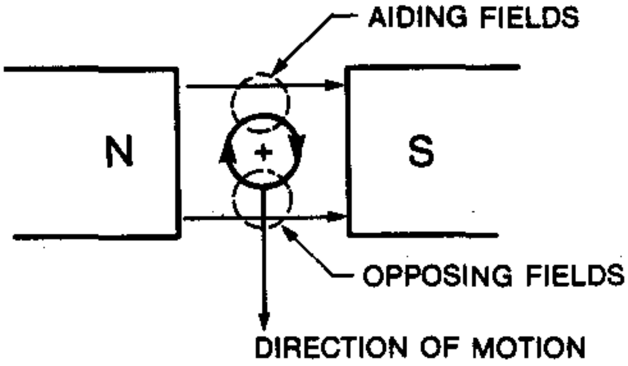

Figure 4: Interaction of the Two Magnetic Fields and the Resultant Direction of Motion

The above analysis can be applied, if the direction of the current through the conductor is changed. See Figure 5.

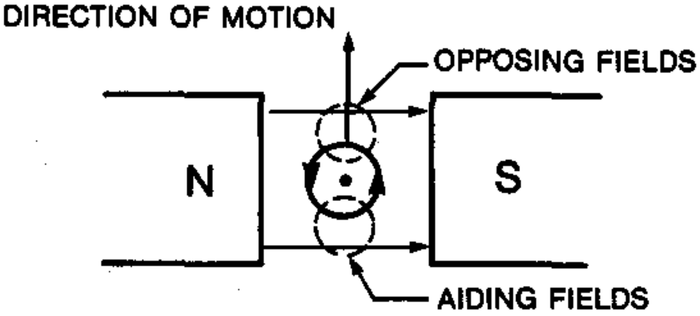

Figure 5: Upwards Motion of Conductor With a Change in Current Direction

Now consider a conductor in loop form. See Figure 6. Note the following:

- Current from the supply goes through one side of the loop and returns through the other side. Hence, the direction of current through each side of the loop is different.
- The direction of magnetic fields around each side are different.
- The direction of motion on each side is different.

If the conductor loop is mounted on a shaft through its centre as shown in Figure 6, and the shaft is mounted on bearings at the two ends, the conductor and the shaft will rotate.

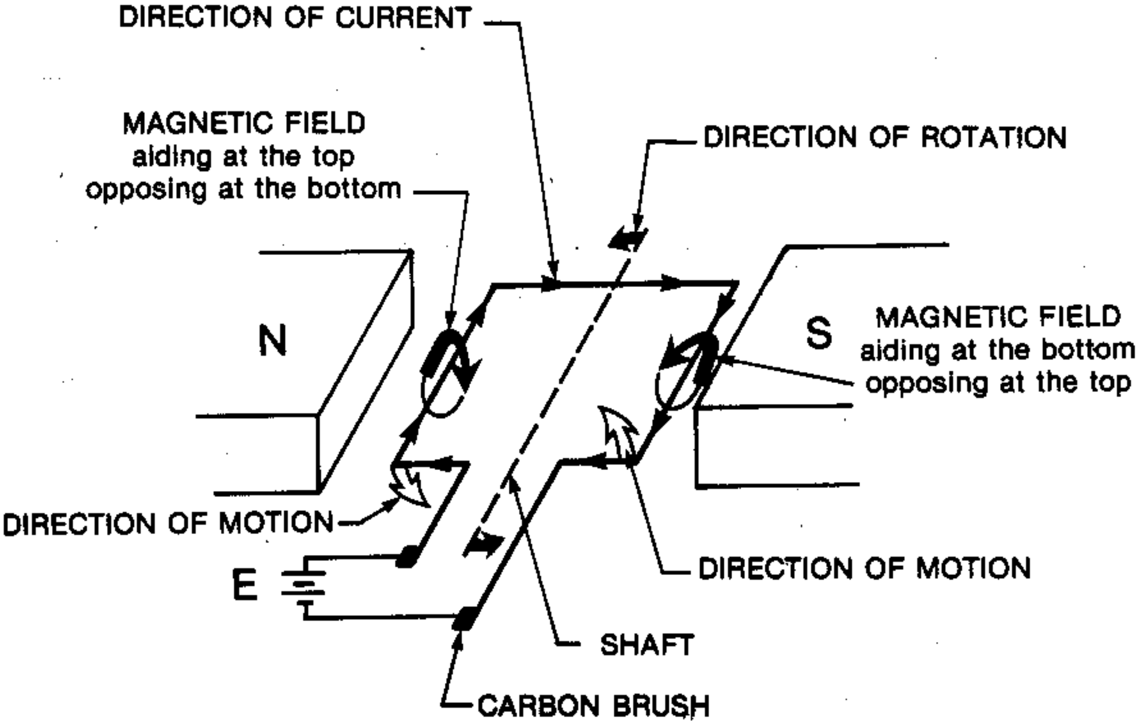

Figure 6: Current Supplied to a Loop and The Resulting Direction of Motion

3.1 Electromagnetic Force (continued)

The magnetic force produced, to cause the rotation of the shaft, is expressed below:

$$F(\text{newtons}) = B \cdot I \cdot L \text{ (do not memorize)}$$

where:
F is the force produced by the interaction of the two magnetic fields, in Newtons.
B is the magnetic flux density of the permanent magnet, in Teslas.
L is the length of the conductor in the magnetic field, in metres.
I is the magnitude of current flow through the conductor in amperes.

The above presentation explains the operation of a DC motor.

3.2 AC Motor

Mechanical motion is still produced in an AC motor by the interaction of two magnetic fields. However, how the two fields are obtained is different and is explained in the sections below.

Rotating Magnetic Field

When a three phase supply is connected to the stator of an AC motor, a resultant rotating magnetic field, of constant magnitude is produced. For an explanation, see Appendix A, at the end of this lesson (for information only).

3.3 Rotor Construction

The rotor of an AC motor is made of conductors, which are shorted at the two ends by a short circuiting ring at each end. Figure 7 shows the basic construction of a **rotor of squirrel cage induction motor** (SCIM). This AC motor is referred to as a SCIM because it operates on the induction principle (discussed later) and the way its rotor is constructed.

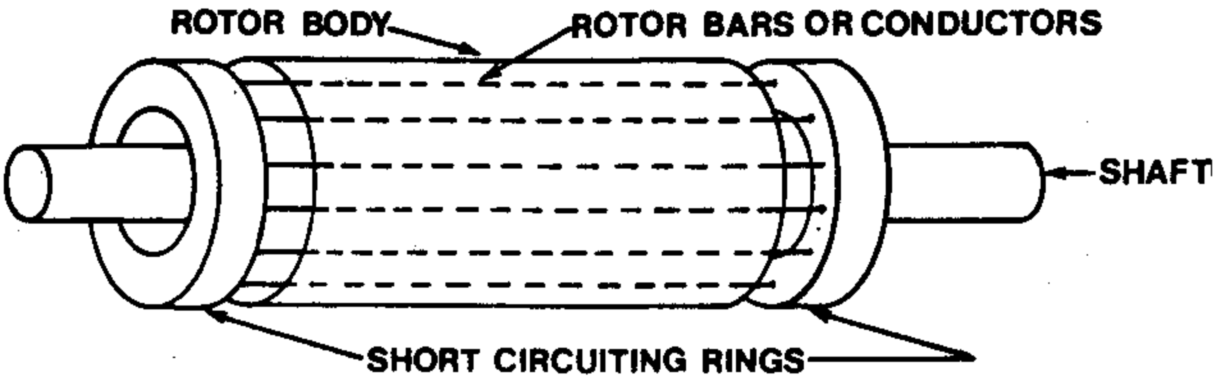

Figure 7: Rotor in an Inductor Motor

With smaller motors, the rotor windings and short circuiting rings are cast directly into the supporting rotor iron. The fan blades are cast onto the short circuiting rings. With large motors, the rotor winding consists of copper bars brazed to copper short circuiting rings. With this design, the fan is usually separate.

3.4 Stator

The induction motor stator windings are inserted and wedged in slots punched in the laminated stator iron. This is a similar arrangement to that used in a generator. The stator iron is securely clamped in the frame of the motor. The bearings are mounted in the end plates. Three phase input power lines are connected to the respective stator windings in a terminal box.

3.5 Rotation of Shaft in an AC Motor

When a three phase supply is connected to the stator windings of an AC motor, a rotating magnetic field is produced, which continually rotates 360°. The rotation of this magnetic field constitutes a "relative motion" between the motionless rotor conductors and the magnetic field. As a result, all the three requirements (conductor, magnetic field and relative motion) are met and a voltage is induced in the rotor conductors.

Since the rotor conductors are short circuited by the short circuiting rings at the two ends, a current flows through the rotor conductors and produces its own magnetic field.

Interaction of the rotor magnetic field and the stator magnetic field produces the rotation of the shaft the same way as explained in Section 3.1

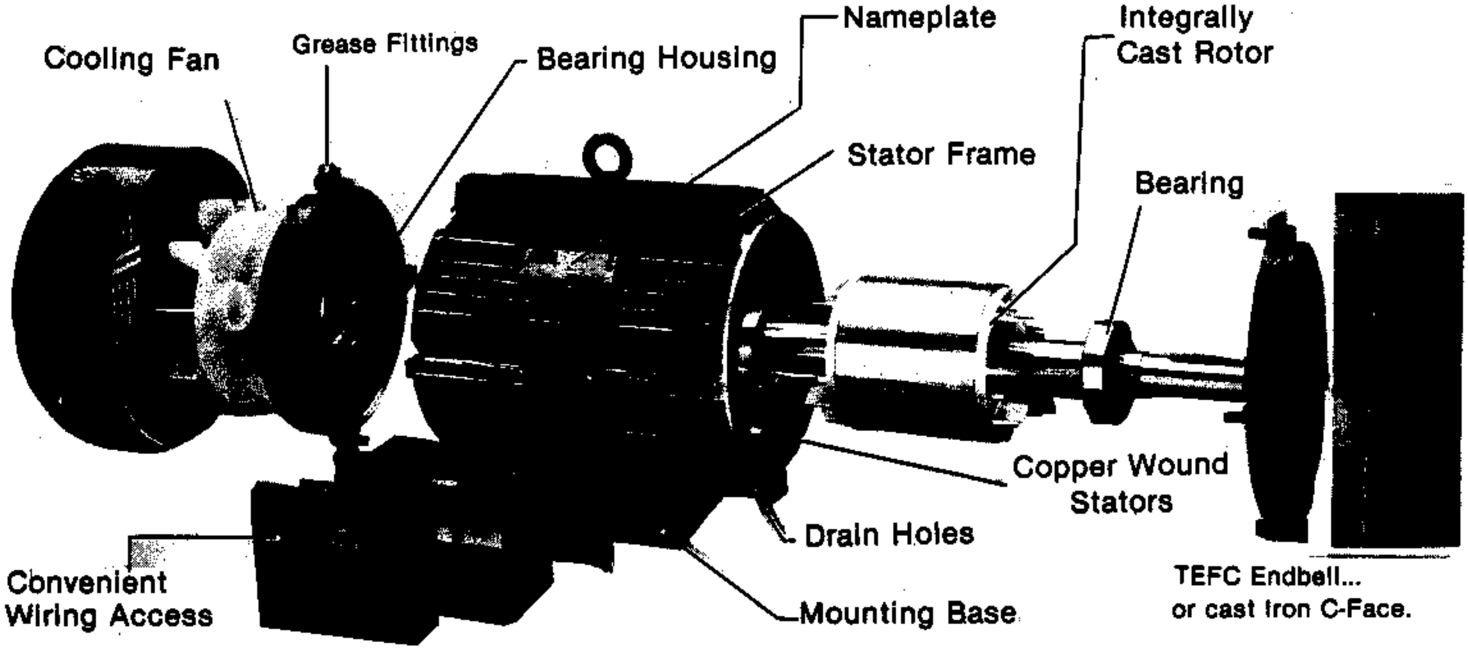

Figure 8: Cutaway View of a SCIM (Squirrel Cage Induction Motor)

4. Motor Torque

The tendency to produce rotation is referred to as **torque.** Figure 9 shows the torque-speed characteristic curves of a motor. The unit of torque is the Newton-meter. The motor running speed and the motor running torque is determined by the characteristics of the load which is coupled to the motor (i.e. a pump). A typical load torque curve is also shown in Figure 9. The motor will always try to deliver the exact amount torque required by the load. This would be where the motor torque and load torque curves intersect.

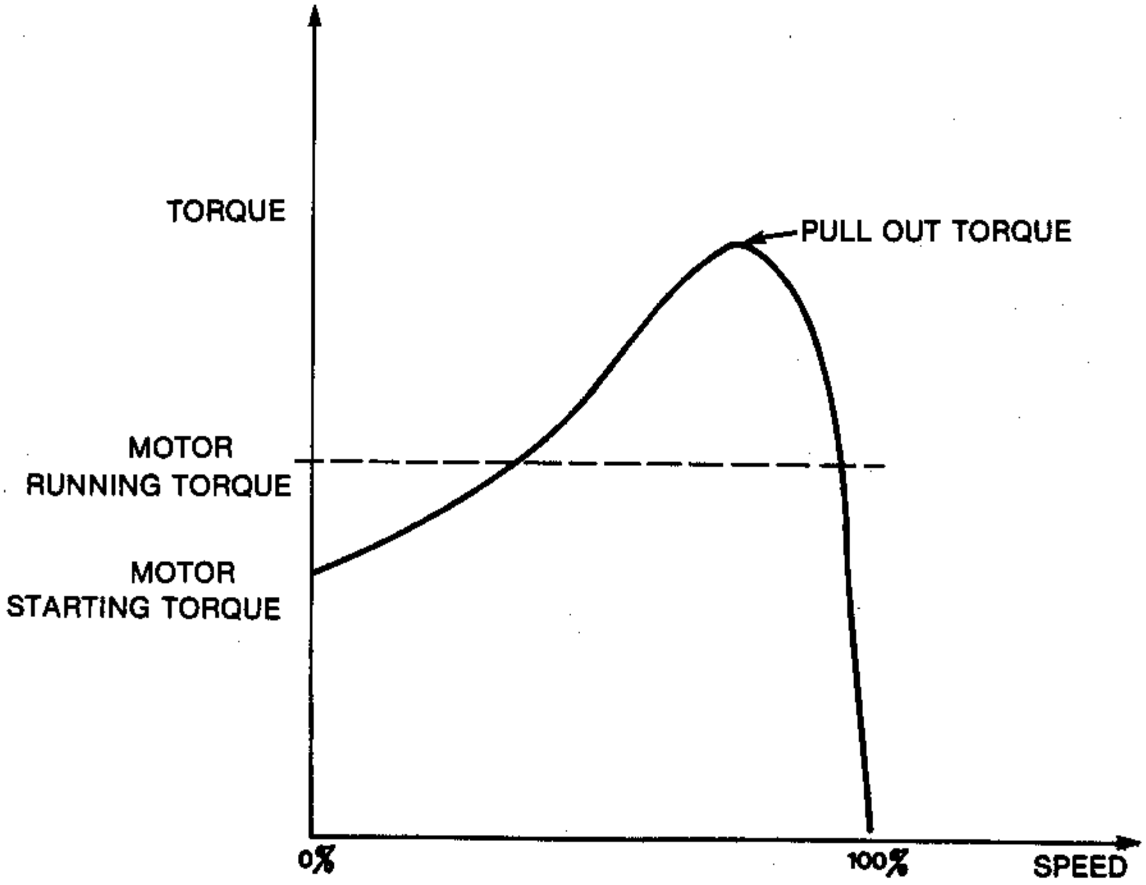

Figure 9: Torque Speed Characteristic Curve of a Motor

4. Motor Torque (continued)

4.1 **Motor Starting Torque:** It is the torque motor delivers when started from standstill position. It is also referred to as **locked rotor torque.**

4.2 **Motor Running Torque:** It is the torque at which the demanded by the mechanical load placed on the motor is equal to the torque produced by the motor. It is the equilibrium point between the mechanical load and the motor.

4.3 **Motor Pull Out Torque;** It is the maximum torque developed by an induction motor at rated voltage and frequency. If the torque demand is increased beyond this point, the motor will stall.

5. Motor Current

Figure 10 shows a chracteristic curve of motor current vs speed. Motor-full load current is the current which the motor draws at the rated voltage, frequency, and torque.

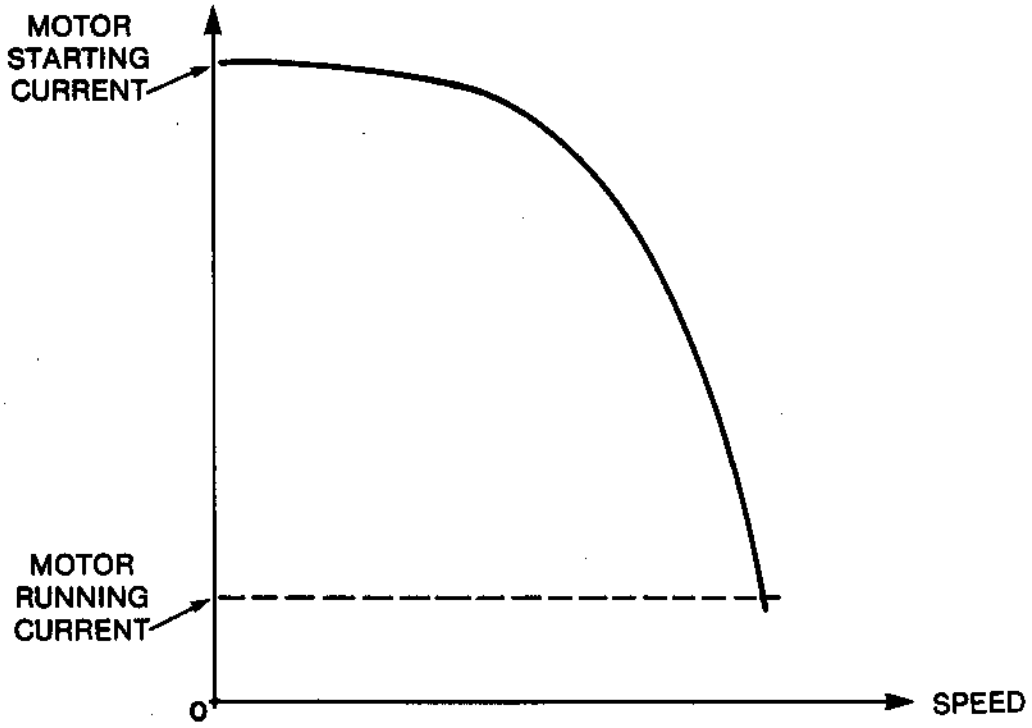

Figure 10: Motor Current vs Speed Characteristics

From the curve shown in Figure 10 it can be seen that the motor draws a large current at starting point. As the motor speed increases, current drawn by the motor decreases.

Motor Starting Current is about six times larger than the motor's full-load current. The exact value depends on the motor design.

6. Synchronous Speed

The speed of rotation of the stator magnetic field is called "**synchronous speed**". Synchronous speed, N_S is calculated by:

$$N_S = \frac{\text{Frequency}}{\text{Number of Pole Pairs}} \text{ revolutions/sec}$$

7. Slip Speed

The rotor of the induction motor follows the rotating magnetic field created in the stator. But, the rotor must always rotate slightly slower than the magnetic field, for the "relative motion" to take place. For idle running, this difference between the synchronous and the actual rotor speed is very small and depends on the friction and windage. The difference between the synchronous speed and the rotor speed is called the **slip speed** or in short **slip** .

Slip is expressed as a % of synchronous speed. Examine the expression below.

$$\% \text{ Slip} = \frac{\text{Synchronous Speed - Rotor Speed}}{\text{Synchronous Speed}} \times 100\%$$

If the rotor could rotate at synchronous speed, the slip would be zero. (This, however, does not occur as explained above). If the rotor is blocked from rotating, the slip equals one or 100%.

8. Motor Operation

Figure 10(B) has the previously mentioned motor torque and motor current vs. speed curves superimposed. Let us examine how they are related.

At stand still an induction motor takes standstill or starting current and produces starting torque. Because the torque produced by the motor is greater than the torque required by the load. The motor and load speed will increase and the current falls. Motor torque will continue to increase until it produces its maximum attainable torque or pull out torque, at which time the torque will begin to decrease with increasing motor speed.

The motor running speed, slip speed and normal running current are all determined at steady state operation. This is at the intersection of the motor torque curve and load torque curve.

As an exercise, the reader should be able to follow the chain of events which would occur in a motor if the demanded load torque were to increase. To visualize this, consider the case where a motor was driving a water pump and the pump bearings are now beginning to deteriorate.

Answer:

The motor would eventually burnout due to excessive heat from current overload. Larger motors are protected against this situation. This will be discussed in the Motor Control section of these notes.

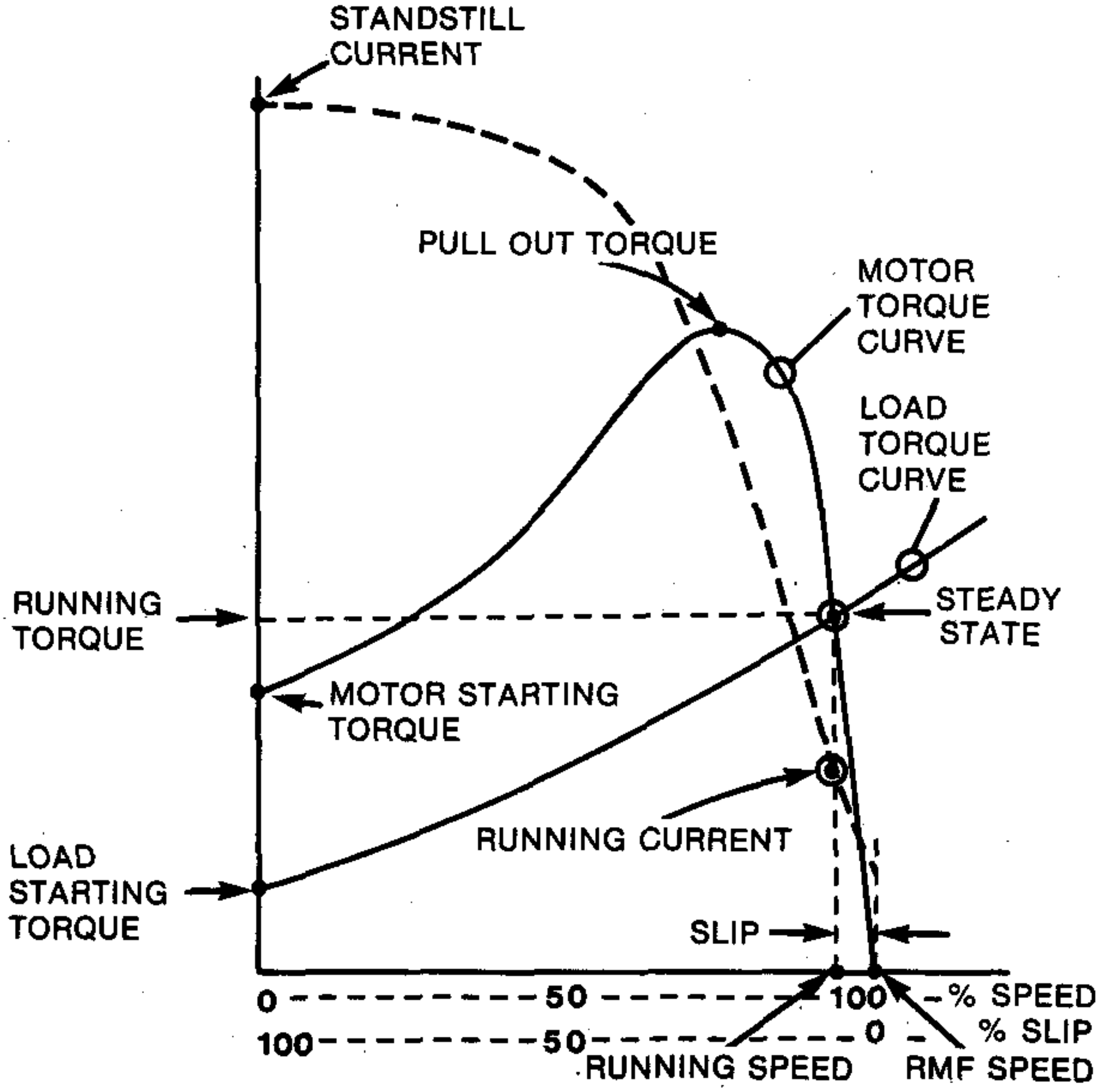

Figure 10(B): Motor Torque and Motor Current Versus Speed For an Induction Motor

6. Motor Nameplate Data

Motor nameplate data provides valuable information about the motor. Some of the most common data that the motor nameplate displays is given below:

(a) HP:	Indicates the horsepower rating of the motor.
(b) RPM:	Indicates the normal operating speed of the motor.
(c) Volts:	Indicates the normal operating voltage of the motor.
(d) Amp:	Indicates the normal operating full load current of the motor.
(e) Cycles:	Indicates the normal operating frequency of the power supply connected to the motor.
(f) Phase:	Indicates the type of motor - 3 phase or single phase.
(g) Service Factor:	Indicates how much overload above its nameplate rating the motor can deliver, continuously.
(h) Power Factor:	Indicates the power factor of the motor at rated current, voltage and frequency.
(i) Time Rating:	Indicates the duty cycle, ie, frequency of start and stop permitted for the motor. A motor rated as **continuous** duty cycle is not suited for frequent starts and stops.
(j) Insulation Class:	Letter associated with this rating corresponds to the temperature rating of the insulation used in the motor. For further explanation see the lesson on "Insulation".

(k) Max Ambient Temp: Each motor is rated to operate at a certain maximum working temperature, at rated HP. This temperature rating depends on the class of insulation used. The working temperatures are based on a standard 40°C surrounding temperature, referred to as the ambient temperature. If the ambient temperature is more than the standard 40°C, then the motor would have to be derated, in terms of HP.

(l) CEMA Designation: Letter associated with this designation indicates the motor speed/torque characteristics, % slip, normal voltage, frequency and starting current of the motor as standardized by Canadian Electrical Manufacturers Association (CEMA).

(m) Frame: Number and letters associated with this designation indicate the physical dimensions of the frame, as standardized by CEMA.

(n) Type: The letter designation associated with this information is the manufacturer's own designation for his own recording convenience. It will vary from manufacturer to manufacturer.

(o) Model: Numbers and letters associated with this designation indicate the model number for a particular manufacturer.

(p) Serial Number: Indicates the serial number assigned to a particular motor.

9. Ventilation System

In an induction motor, heat is produced in three main areas:

(a) **Stator Windings** - Heating (I^2R) is produced by the stator current flowing through the stator windings.

(b) **Stator Iron** - Heating is produced by eddy current and hysteresis losses.

(c) **Rotor Windings** - Heating (I^2R) is produced by the rotor current flowing through the rotor windings. Rotor iron core losses are negligable due to low rotor currents.

There are two basic types of enclosures, namely:

(a) Open.
(b) Totally Closed.

In each type, variations exist depending on the motor application. In each case, the heat is removed by air cooling.

Figure 11 shows the ventilation circuits for an induction motor having open ventilation. Outside air is brought in and circulated over the windings. This type of motor is not suitable for use in damp or dusty environments.

Figure 12 shows the ventilation circuits for a totally enclosed fan cooled induction motor. Note that there are two separate air circuits.

The inner circuit is cooled by conduction through the casing.

The outer circuit cools the outer surface of the casing.

This type of motor is suitable for use in damp or dusty environments.

Ventilation of a motor must not be restricted. Any restriction in air flow will result in the motor getting hotter and this may lead to a burn out.

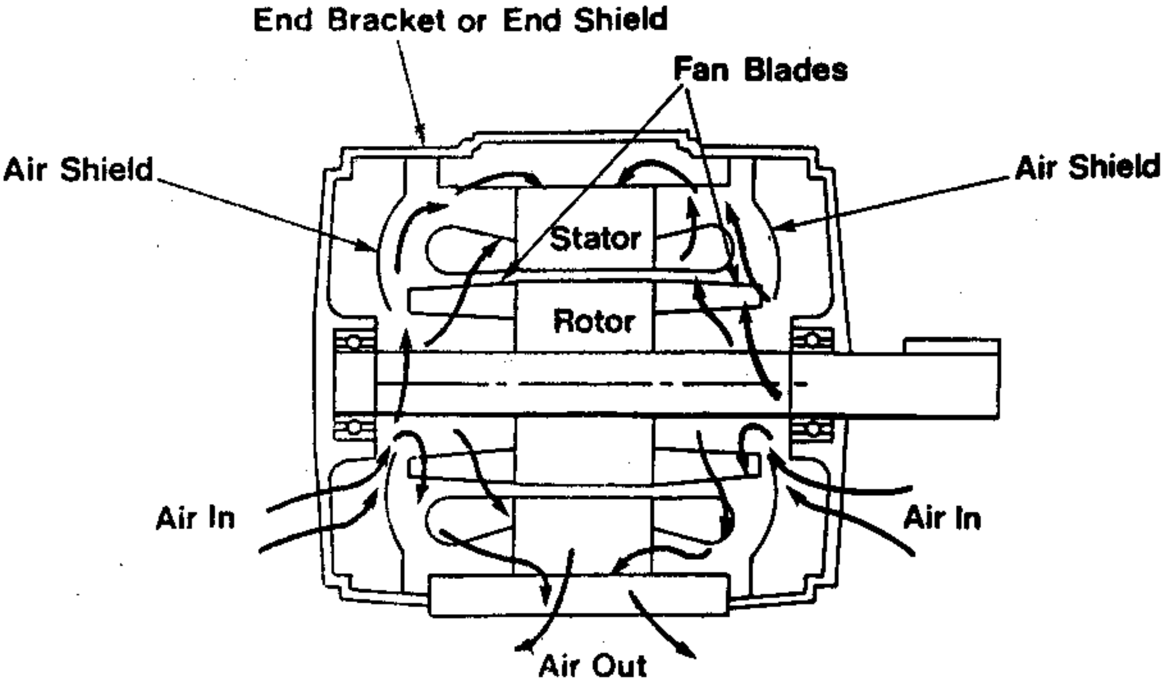

Figure 11: Ventilation Circuits for an Induction Motor Having Open Ventilation

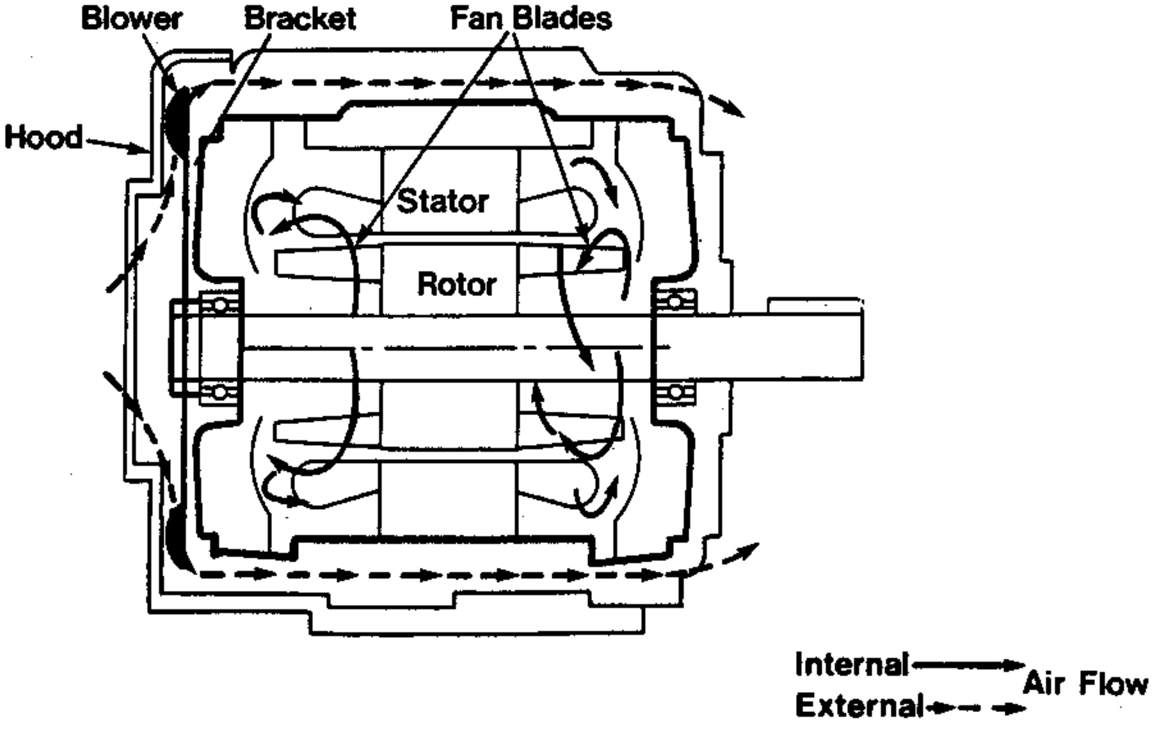

Figure 12: Ventilation Circuits For a Totally Enclosed Fan Cooled Induction Motor

Direction of Rotation and Phase Sequence

10. Three phase power supply connected to the motor must be in the correct phase sequence to provide the correct direction of rotation. If any two leads of the power supply connected to the three phase induction motor are interchanged, phase sequence will be reversed and the motor will rotate in the opposite direction.

Notes

ASSIGNMENT

1. What is a motor. What form of energy is input and output for a motor? (Section 2)

2. Explain how shaft rotation is obtained in a squirrel cage induction motor (SCIM).

3. What is the purpose of the short circuiting rings in the rotor of a squirrel cage induction motor (SCIM)? (Section 3.3)

4. Draw and properly label the following curves for an induction motor.

   (a) Torque vs speed.

   (b) Current vs speed.

5. Define the following terms, as related to squirrel cage induction motors. (Section 4)

   (a) Torque

   (b) Starting Torque

   (c) Running Torque

   (d) Pull Out Torque

6. What is the relationship between the starting current and the full load current in a squirrel cage induction motor (SCIM)?

7. Define the following terms, as related to a squirrel cage induction motor:

   (a) Motor full load current. (Section 5)

   (b) Synchronous speed. (also give the mathematical expression to calculate synchronous speed of a squirrel cage induction motor) (Section 6)

   (c) Slip speed. (also give the mathematical expression to calculate the slip speed) (Section 7)

8. Interpret the following nameplate data for a squirrel cage induction motor. (Section 8)

   (a) HP

   (b) RPM

   (c) Volts

(d) Cycles

(e) Amp

(f) Phase

(g) Service Factor

(h) Power Factor

(i) Time Rating

(j) Insulation Class

(k) Maximum Ambient Temperature

(l) CEMA Designation

(m) Frame

(n) Type

9. What two general types of motor enclosures are available. Give their respective applications. (Section 9)

10. How do the two types of motor enclosures differ from each other, in providng cooling to the motor. (Section 9)

11. What is the consequence of changing the phase sequence, in a three phase induction motor? (Section 10)

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